DEVELOPMENT OF A LIGHTWEIGHT, MULTI FUEL-CAPABLE, 30-kWe APU FOR NON-PRIMARY POWER

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ABSTRACT

A methodology for rapid development of purpose-built, heavy-fueled engines is being created. The methodology leverages best-in-class computational tools, component supplier expertise, user-programmable ECUs, and rapid prototyping to quickly provide custom engines for demanding military applications. . First-tier automotive suppliers are being used extensively on non-complex standard components to reduce the development time. Our design methodology aggressively eliminates unnecessary components and incorporates various other weight-saving features to minimize system weight. The anticipated total development time to a working prototype is less than 15 months for this first iteration of the methodology, and will be further reduced for any subsequent design iterations.

INTRODUCTION

An approach was taken in the development of a 30 kWe APU for multiple applications that is highly modular and yields an ultra lightweight, versatile package. The conventional approach to military generator/APU development is to couple a commercially available engine with a commercially available alternator and power electronics. As a result, the current 30 kW standalone generator weighs 3006 lbs (NSN 6115-01-274-7389) [1]. The current approach will yield an estimated order of magnitude decrease in this value by incorporating many weight saving features such as integrating the alternator, starter and the flywheel, integrating the intake manifold into the head, reducing the size of the engine, and lightweight framing. Additionally, commercial off-the-shelf components drastically reduce the development time for the engine, alternator and power electronics. In fact, within 7 months the detailed engine design is nearly complete with the fabrication of a prototype system already commenced. Figure 1 shows a CAD rendering of the engine.

The design for this particular engine/APU was performed to allow scaling by either the number of cylinders or geometric size to yield a family of APUs that are extremely lightweight and are purpose-built with a very short development time. The components designed in-house are developed using state-of-the-art CFD and FEA tools, reducing the number of costly prototype iterations required. This paper will first describe the methodology of the engine design; highlight a few key weight- and space-saving features of the engine; describe the computational tools used; and finally, describe the block and head design methodology.

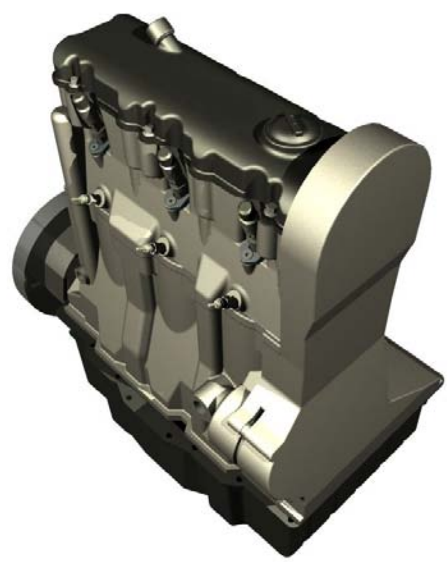

Figure 1: Engine that Powers the 30 kW APU

OVERALL METHODOLOGY

For this particular engine/APU development, an “inside-out” approach was used, whereby the crankcase components serve as the building block for the remainder of the engine/APU. The engine design began with the design/selection of the crankcase components using the crankshaft as the initial building block. Next, the interior engine components were selected including the piston and

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the connecting rods. Finally the head components were selected based on the decisions made for the piston and approximate desired breathing characteristics. Once all of the components were selected, the head and the block were designed using a "wrapping" method which is described later.

The engine also incorporates features for enhanced operation and reliability. For instance, the engine will be beltless, to improve the reliability of the engine by eliminating the belt failure mechanism. It also features an advanced, automotive-based common rail injection system to allow the use of different fuels. The electronic control of the common rail system allows the injection timing and pressures to be modulated, controlled by important fuel characteristics such as density, viscosity, and cetane number.

UNIQUE FEATURES

In the course of using the design methodology, two key features were included to reduce the overall size and weight of the engine, as well as reduce the part count of the engine. Figure 2 shows the crankcase components. In typical three-cylinder engines, the required balancing shaft and oil pump are packaged together in a large module and placed either below or to the side of the crankshaft. In contrast, in the patent-pending, compact design that was developed, the counterweights for the balancing shaft and the crankshaft interweave so that the balancing shaft can be packaged much closer to the crankshaft. Additionally, the oil pump shares a common shaft with the balancing shaft and is placed on the non chain-drive end of the engine. Overall, this yields a much smaller package, reduces the weight as well as the part count for the overall engine. This unique configuration evolved based on available mating components, and computational investigations.

Figure 2: Crankcase Components including Oil Pump/Balancing Shaft

Figure 3 shows a rendering of the engine head. For this design the intake manifold is integrated into the head. With this method, the head and the intake manifold are part of the same casting. This feature reduces the size of the overall APU package slightly (2-5 mm), but more importantly, reduces the part count, cost, and complexity of the engine. The integrated intake manifold and the balancing shaft/oil pump arrangement are two of the features that significantly improved the design of the engine. These features, as well as all other custom components, were then further-refined using state-of-the-art computational tools.

Figure 3: Rendering of the Head Showing the Integrated Intake Manifold

COMPUTATIONAL METHODOLOGY

The engine utilizes standard (off-the-shelf) components for a large number of the engine components and subassemblies. This includes but is not limited to piston assemblies, valve train components, mounting hardware, and oil filters. However, for each purpose-built engine/APU there are inevitably components that are unique to the engine; this includes the crankshaft, head, block, camshaft, and manifolds. For these engine specific components, designs begin with guidelines found in the open literature, and then evolve with mating requirements with other components and necessary geometric and material changes identified from our computational results. Additionally, these engine specific components are developed working closely with suppliers that manufacture them. For this effort, modeling and simulation software was used for in-cylinder CFD and FEA analysis.

In-Cylinder CFD

The software that was used for all of the in-cylinder CFD calculations uses cut-cell technology and forced orthogonal gridding with adaptive mesh refinement (AMR) and grid embedding that enables the code to fully generate the mesh

instead of requiring extensive user input. With this capability, a single user can work on independent parts of the engine design in parallel with the in-cylinder CFD because the user setup time is drastically less than more conventional CFD approaches.

Figure 4 shows a contour of velocity at the mid-plane of the cylinder near TDC with the different meshing densities at different locations and also a tight grid around high gradient locations of both temperature and velocity. In this particular image, grid embedding is seen below the intake valve. The gradient of velocity at the edge of the jet issuing into the cylinder induces the AMR to add extra cells for a more accurate calculation over the high gradient region. Examination of the swirl number and the inclusion of head components such as the injector and the glow plug guided the evolution of the intake port.

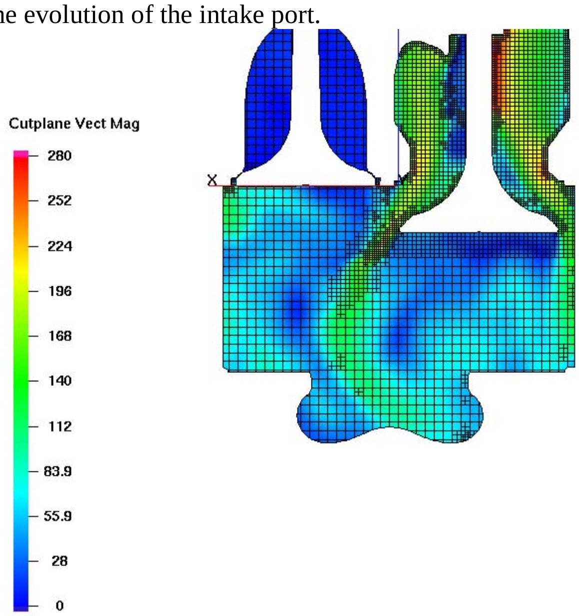

Figure 4: Velocity Contour at the Cylinder Mid-plane during the Intake Stroke

Table 1 shows the evolution of the swirl ratio at the start of injection through the cases run to date. The swirl ratio is defined as [2]

$$\text{swirl ratio} = \frac{\omega_z}{\omega_{crank}} \quad (1)$$

where z is the axis of the cylinder, ω_z is the angular speed around the z axis, and ω_{crank} is the angular speed of the crankshaft. The swirl ratio is a measure of the strength of the axial vortex which is the main predictor for mixing rate, jet penetration, and also influences the heat-release rate.

During these runs, the valve lift profiles and timing were altered, the injection timing was changed, and the engine speed was changed. The difference between Case 2 and Case 3, as well as the difference between Case 6 and Case 7, show the effects of the three different intake port geometries that have been investigated. In both comparisons, the swirl number increased. The increased mixing due to the enhanced swirl ratio resulted in quicker heat release and an increase in power output. The brake power specification for this engine is 45 kW (60 hp) to account for mechanical to electrical conversion efficiencies and altitude de-ration. Case 9 demonstrates a power output of 45.7 kW confirming that the hardware choices can yield the required power.

Table 1: Swirl Ratio Evolution vs. Case Number

Case	Swirl Ratio	Speed (RPM)
1	5.01	3600
2	5.36	3600
3,4,5,6	5.53	3600
7,8	5.85	3600
9	5.67	4500

Figure 5 shows the cylinder at 14 degrees after TDC with the spray issuing into the cylinder with a contour of temperature (K). As has been reported by other authors [3], the penetration length for the spray reaches a steady state value at the point when the evaporation rate matches the injection rate. For this particular geometry, the penetration length is always shorter than the radius of the re-entrant lip and therefore allows for a larger number of acceptable spray angles. This analysis is used to determine the placement of the injector and the timing of the injection to minimize the spatial non-uniformity at the surface of the piston.

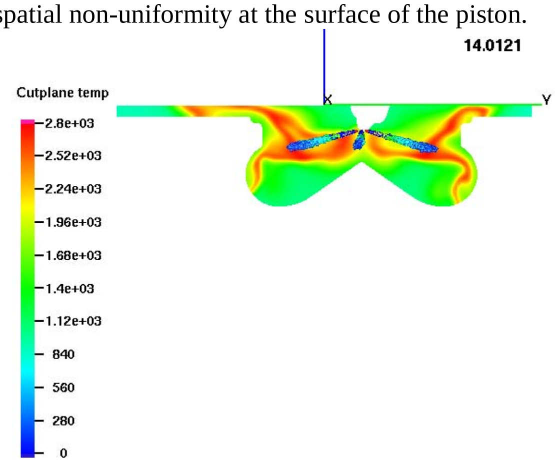

Figure 5: Temperature Contour with Spray at the Centerline of the Piston Bowl

Component FEA

The engine specific components (crankshaft, balancing shaft, block, head, etc.) were first designed using established

engine design guidelines and then fine tuned using FEA. As an example of the type of FEA analysis performed the oil pump body is discussed. Figure 6 shows the boundary conditions that are imposed on the oil pump body. The values for the loads were given based on the maximum operating speed (5000 RPM), the maximum fluid pressure within the pump, and the worst-case of bolt pre-tensioning. Figure 7 shows the resulting static deformation of the oil pump body. The mating of the oil pump to the block was constrained by the balancing shaft design, the stability need at the joint, and the selected material is 356 T6 cast aluminum. The total deformation is 0.009 mm, which is well within the tolerance of the bearings for the pass through shaft. Similar analysis is done for all of the engine specific components using a global factor of safety of 1.5.

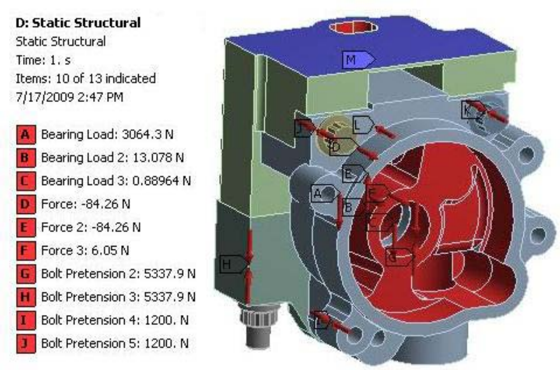

Figure 6: FEA Boundary Conditions for the Designed Oil Pump Body

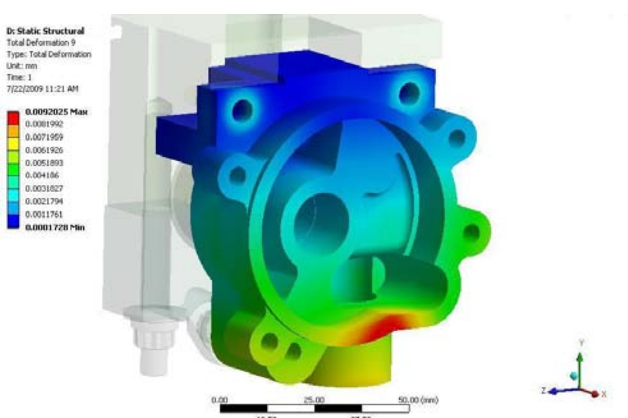

Figure 7: FEA (Displacement) of the Designed Oil Pump Body

BLOCK AND HEAD DESIGN METHODOLOGY

The block and the head design for this engine was done with a "shell" methodology. First, the unavailable material space is defined by the components that will be within the block or head. Next, a buffer amount of material is allotted around the components of required wall thickness (4-6 mm). Finally, the available space for the cooling jackets, and oil passages is sectioned off to provide a full negative volume. A skin is wrapped around this negative volume to give the final design for the larger component (block or head). Figure 8 shows the full negative volume for the head. The blue volumes are for the intake ports and runners, the red volumes are for the exhaust ports, the black volumes are for the oil passages, and the gray volumes are for the head component hardware. Figure 9 shows the final design of the head with the wrapped negative volume shown in Figure 8. Additionally, this design is almost completely modular, both in number of cylinders as well as characteristic dimensions. Therefore, the developmental time is greatly reduced using this system. For this purpose-built engine/APU, the cylinder spacing is set at 101.5 mm and the bore is 79.5 mm.

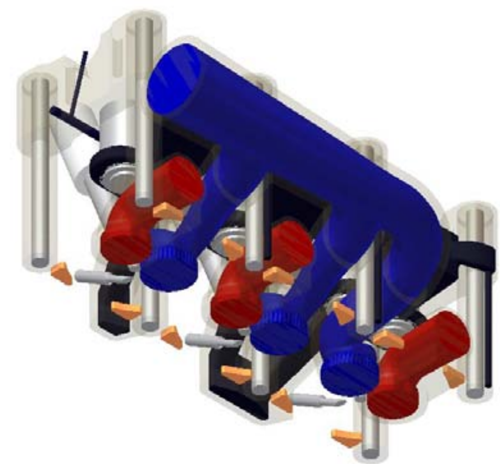

Figure 8: Full Negative Volume for the Head

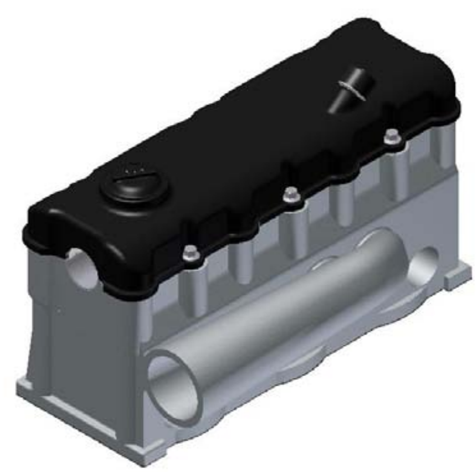

Figure 9: Final Design for the Head

CONCLUSIONS

A novel design approach is being used to drastically reduce the development time of purpose-built engines/APUs. The full system design and integration is a paradigm-changing approach to military APUs that typically relies on commercial, off-the-shelf engines mated to large industrial alternators.

A candidate purpose-built engine is developed, which has a patent-pending balancing shaft arrangement to reduce size, an integrated intake manifold to reduce part count, and a large number of commercially available automotive components to ensure high performance and maintainability. Our approach uses CFD and FEA simulations to reduce the development time of engine specific components, and an innovative wrapping block and head design adaptable to nearly any choice of component hardware.

As a result of this approach, a full design is nearly completed and has already begun prototype construction only 7 months after starting from "a blank sheet of paper".

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